10 μm

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on Advanced Ceramics and Composites

Thermochemical interactions of yttria-stabilized zirconia and molten lunar regolith simulants

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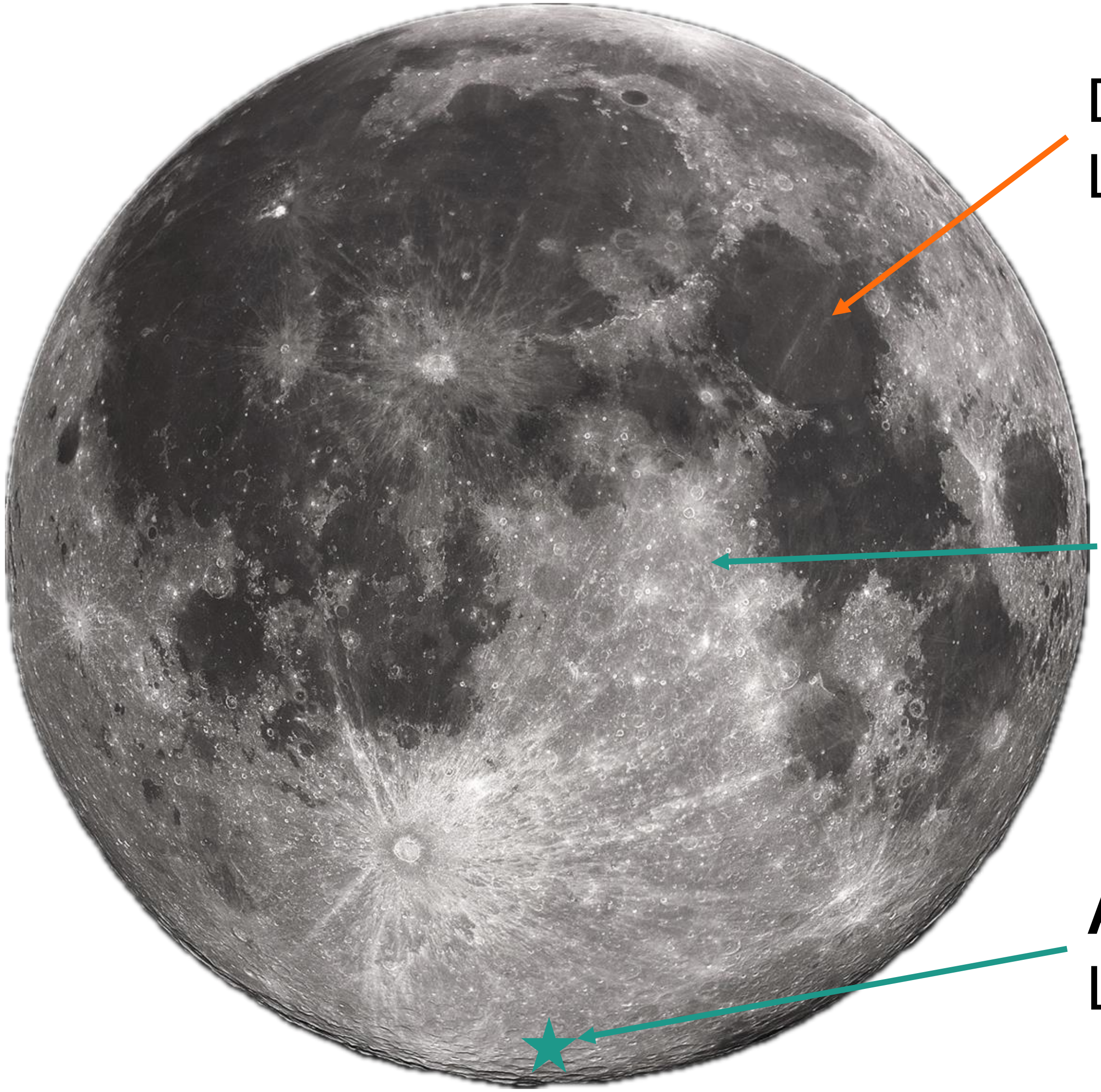
Lunar surface



Dark regions:
Lunar maria

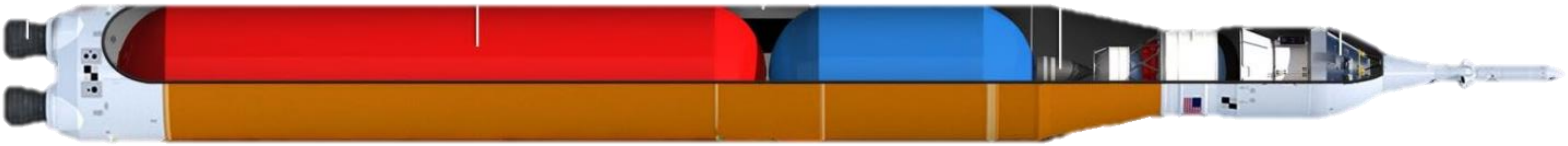
Bright regions:
Lunar highlands

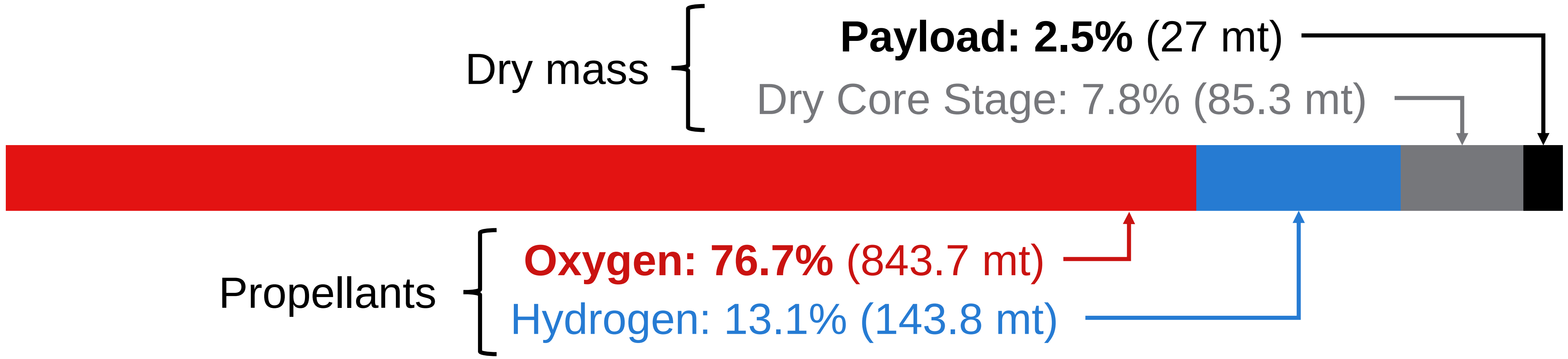
Artemis 3:
Late 2026

Lunar regolith:
Surface layer of granular oxide minerals and glasses

Image from Wikipedia

Space Launch System – Artemis 3

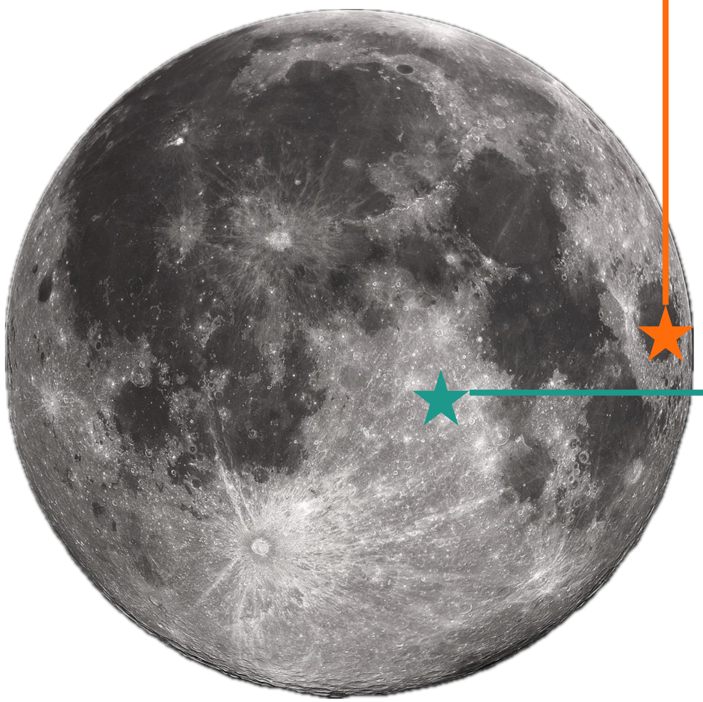




Refueling 27 mt (3%) with lunar-derived oxygen → Drops $/kg of payload by half

https://www.nasa.gov/humans-in-space/space-launch-system/sls-fact-sheets/

Lunar regolith composition



Maria regolith composition [wt%]								
Species	SiO_2	**FeO**	MgO	CaO	Al_2O_3	TiO_2	Na_2O	K_2O
Luna 24	44.6	**20.8**	11.0	10.9	10.8	1.0	0.2	0.0

Regolith compositions similar to CMAS

Highlands regolith composition [wt%]								
Species	SiO_2	**FeO**	MgO	CaO	Al_2O_3	TiO_2	Na_2O	K_2O
Apollo 16	45.4	**4.5**	4.4	16.8	27.9	0.5	0.4	0.1

Lunar regolith is ~40 wt% oxygen → ideal feedstock for oxygen production

Humbert, M.S. et al. *Planet Space Sci.* ***219*** (2022).

Oxygen production from lunar regolith

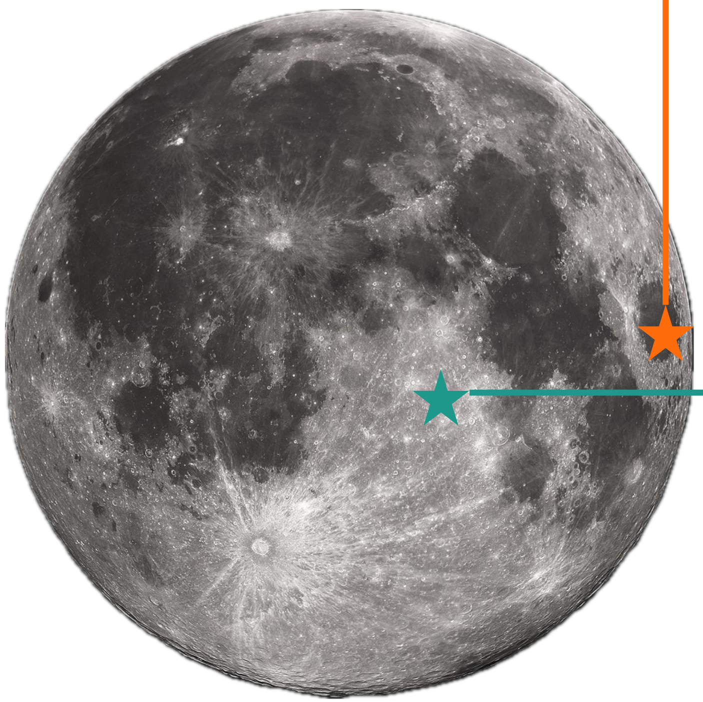
	H_2 reduction	Carbothermal reduction (CH_4)	Molten regolith electrolysis
Site specificity	Moderate to high (ilmenite/pyroclasts)	Low to moderate (iron oxides and silicates)	
Extraction temp.	Moderate (900°C)	**High (1600°C)**	**High (1600°C)**
Energy per kg	High	Moderate	Moderate
Extraction efficiency	1-5%	5-15%	20-40%
TRL	4-5	4-5	2-3

Increasing extraction efficiency

What material can withstand 1600°C and contact with corrosive molten regolith?

YSZ is a promising option based on TBC/CMAS literature

Lunar regolith simulants



Maria regolith/simulant composition [wt%]								
Species	SiO_2	**FeO**	MgO	CaO	Al_2O_3	TiO_2	Na_2O	K_2O
Luna 24	44.6	**20.8**	11.0	10.9	10.8	1.0	0.2	0.0
JSC-1A	48.7	**11.0**	9.2	10.6	15.3	1.6	2.8	0.8

Highlands regolith/simulant composition [wt%]								
Species	SiO_2	**FeO**	MgO	CaO	Al_2O_3	TiO_2	Na_2O	K_2O
Apollo 16	45.4	**4.5**	4.4	16.8	27.9	0.5	0.4	0.1
LHS-1	51.8	**2.7**	1.6	12.9	26.9	0.6	2.9	0.5

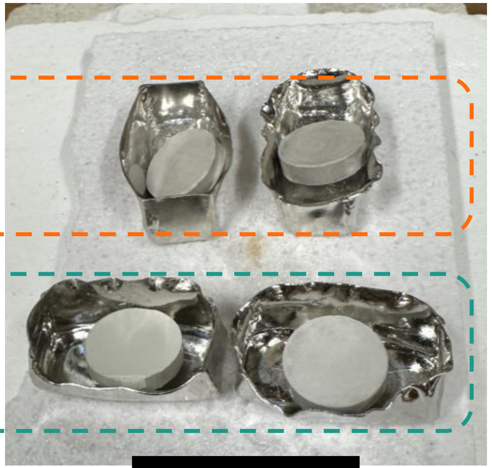
Two simulants selected → JSC-1A for maria and LHS-1 for highlands

Humbert, M.S. et al. *Planet Space Sci.* ***219*** (2022).

Powder compact summary

YSZ + JSC-1A

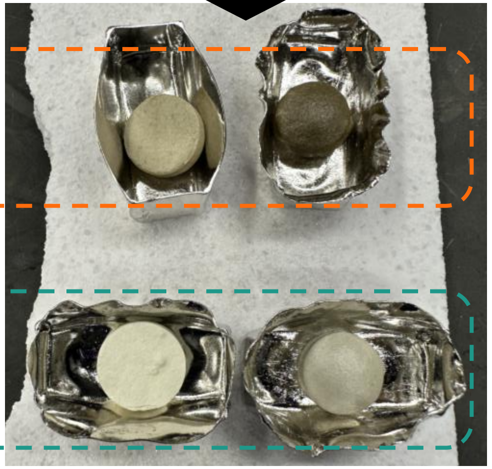
YSZ + LHS-1



1600°C
3 hours

YSZ + JSC-1A

YSZ + LHS-1



Interactions observed:
- YSZ dissolution
- Y depletion from YSZ

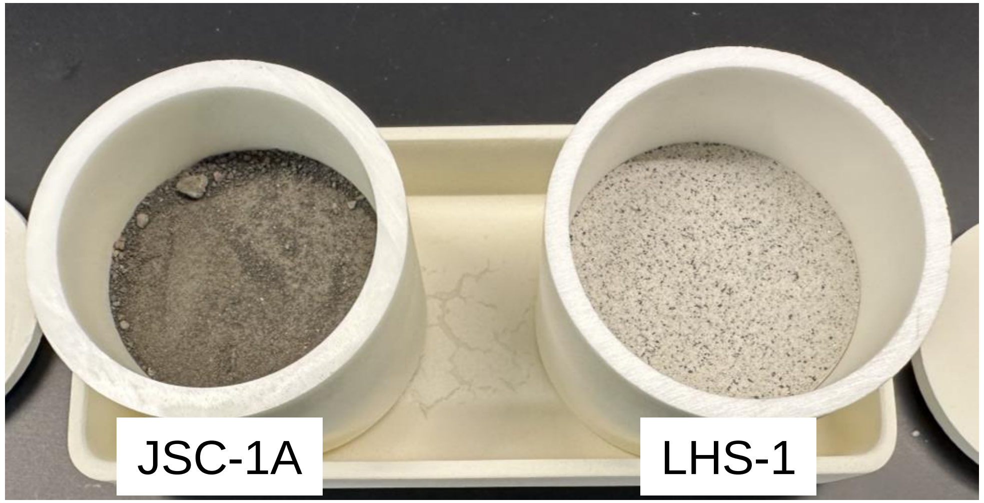
Not observed:
- High temperature reaction phase ($ZrSiO_4$)

	LHS-1 (Highlands)		JSC-1A (Maria)	
	Zr at%	Y at%	Zr at%	Y at%
Measured	1.38	1.27	1.65	1.38
FactSage	1.96	-	1.95	-

Similar Zr/Y solubilities for LHS-1 and JSC-1A

FactSage viscosity model (melts) → LHS-1: 6.7 Pa*s; JSC-1A: 0.7 Pa*s

Crucible experiment



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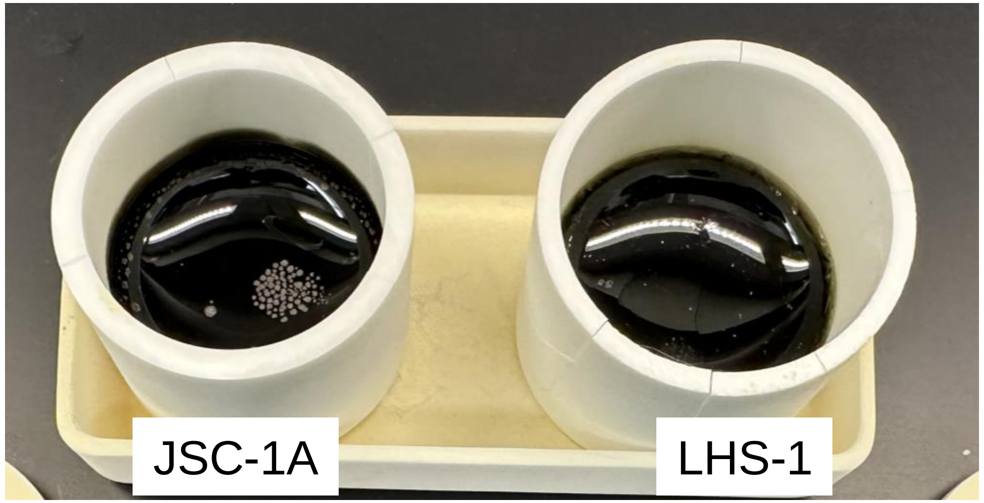
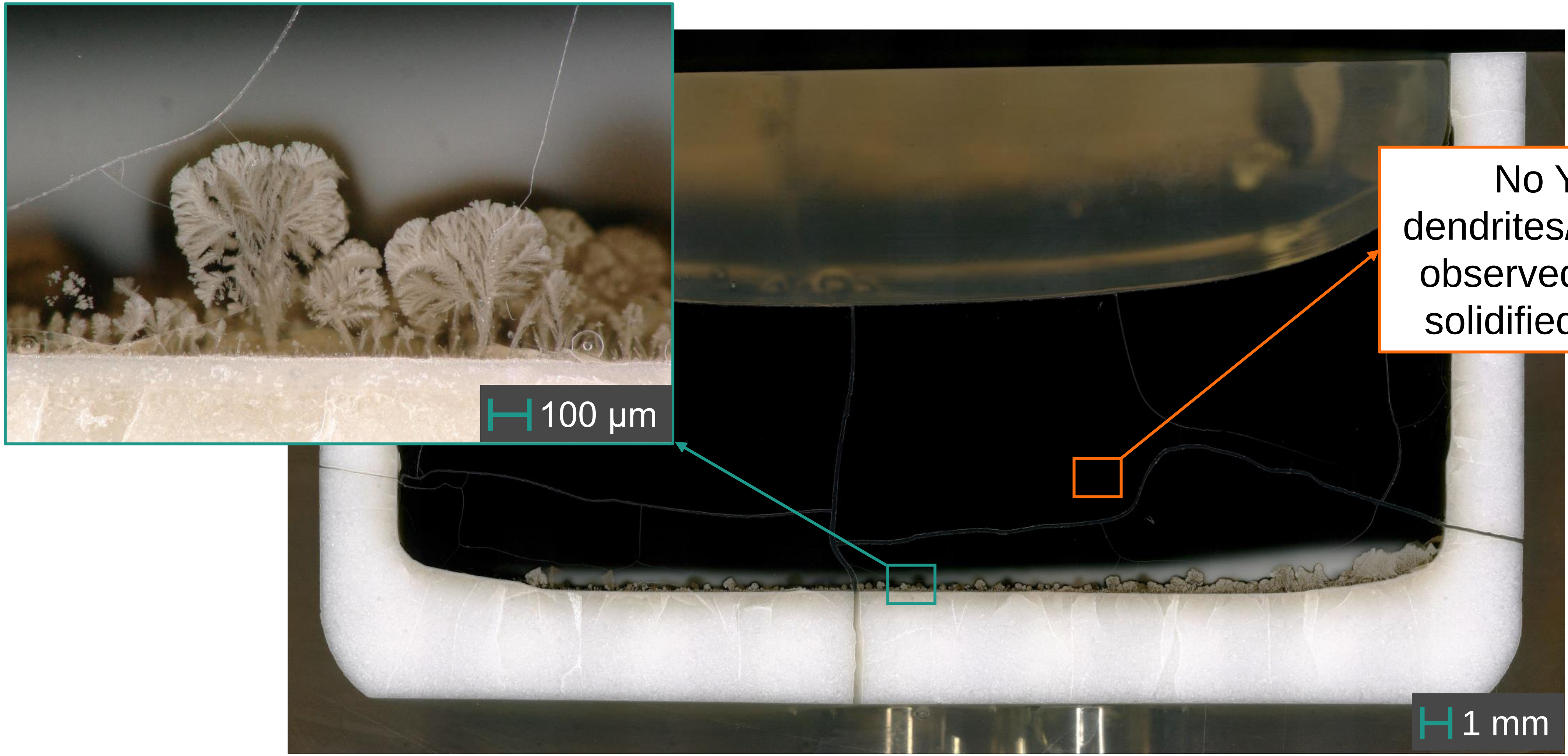


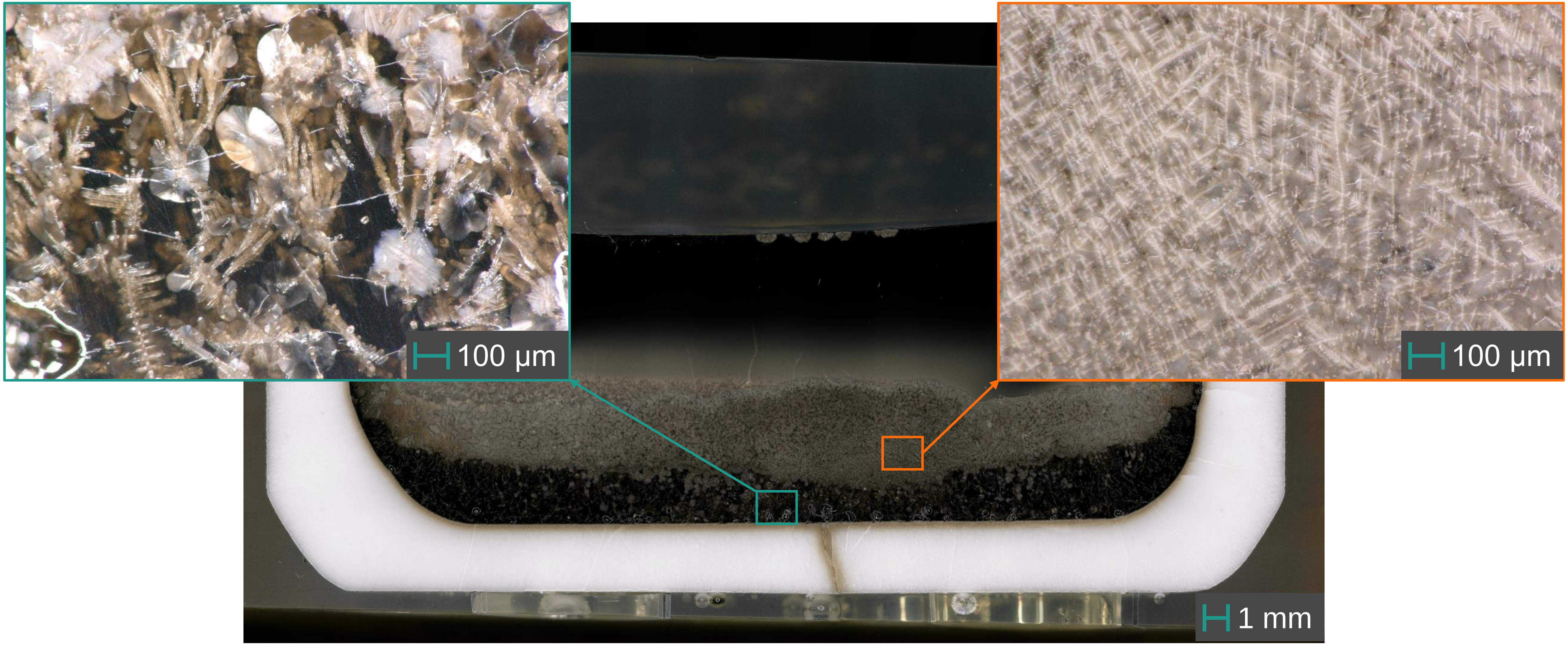
- 8mol% YSZ crucibles used for containment/reactivity testing
  - LHS-1 (highlands) and JSC-1A (maria) simulants tested

Crucible experiment – LHS-1



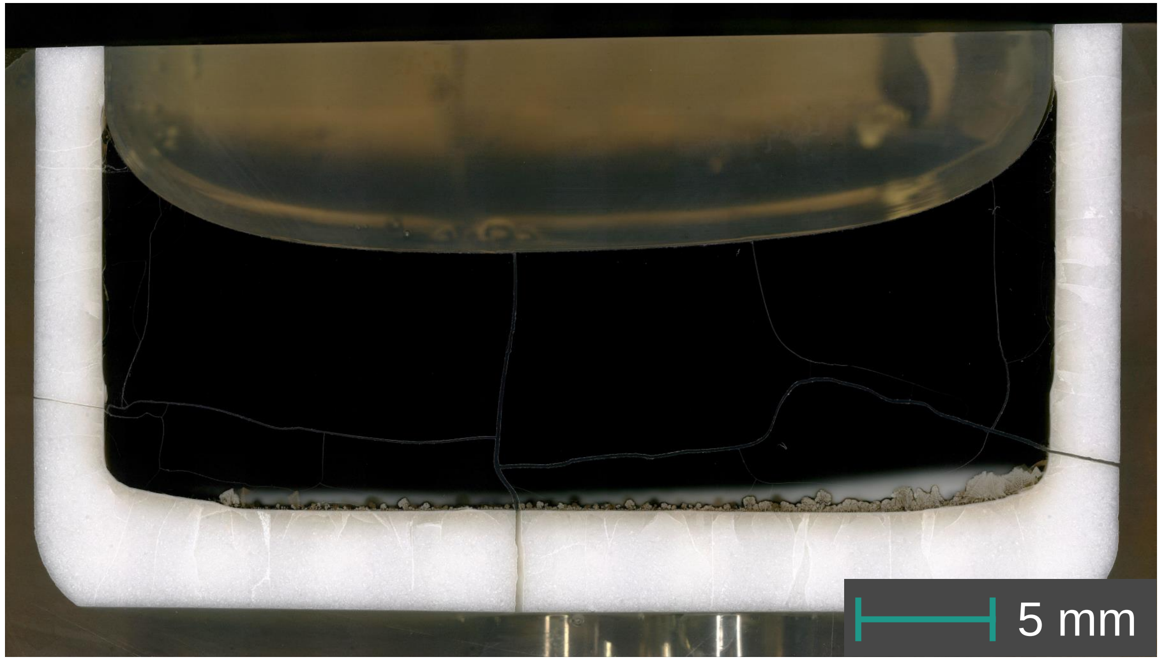
No YSZ dendrites/particles observed in bulk solidified LHS-1

Crucible experiment – JSC-1A

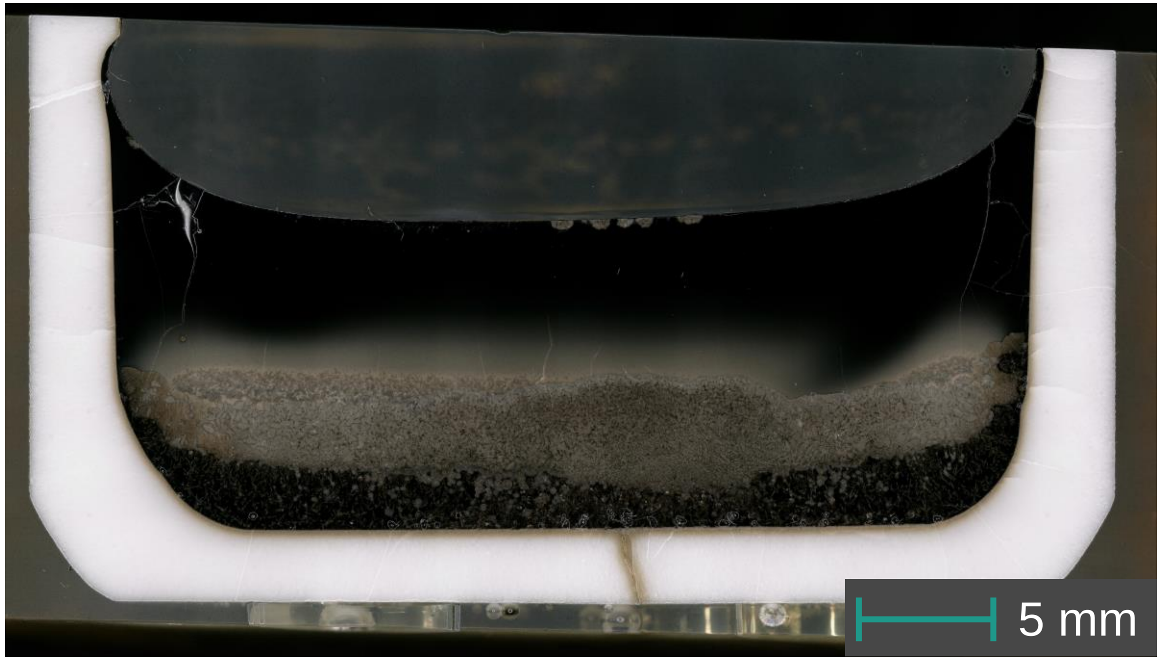


Crucible experiment comparison

LHS-1 (Highlands)



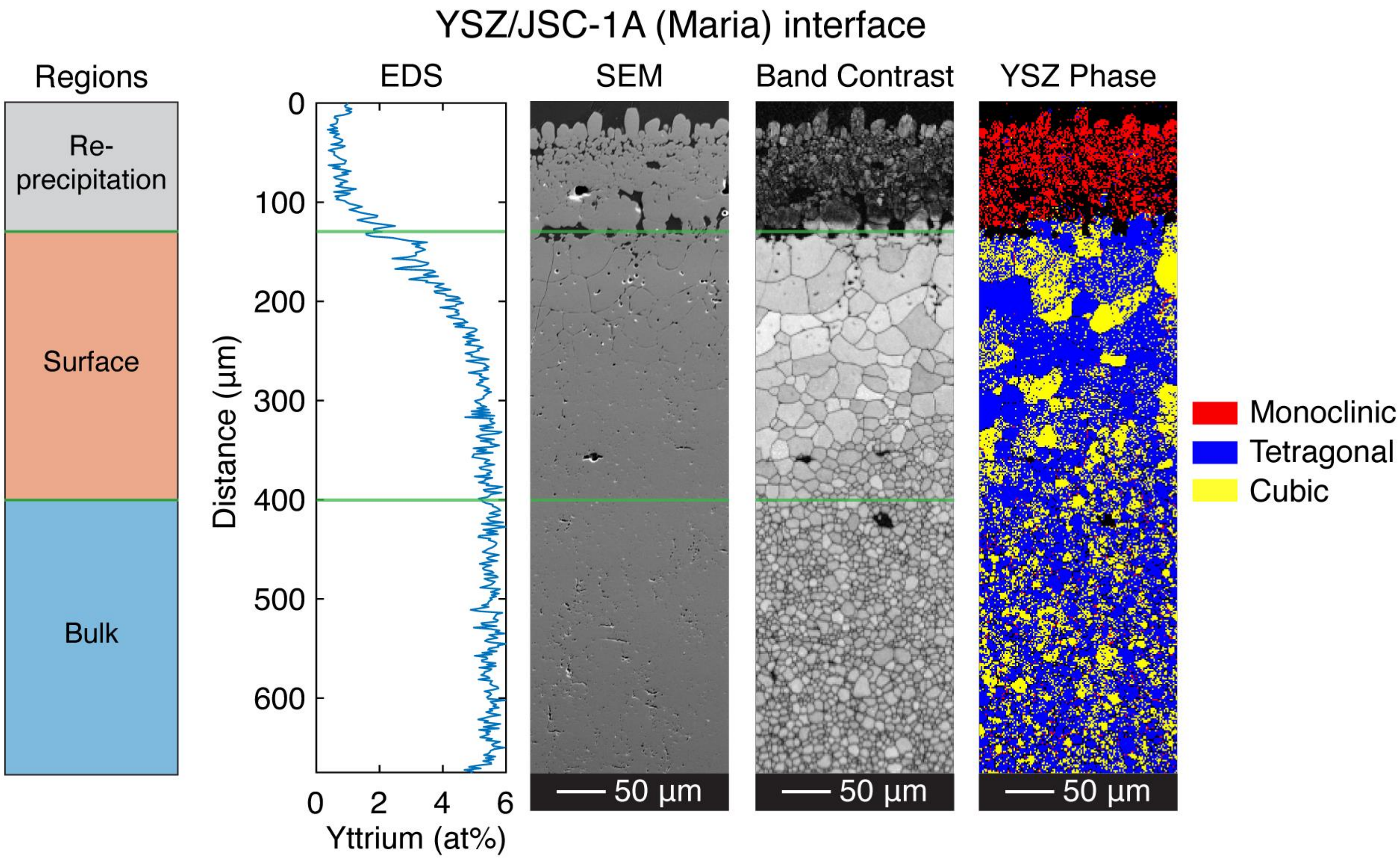
JSC-1A (Maria)



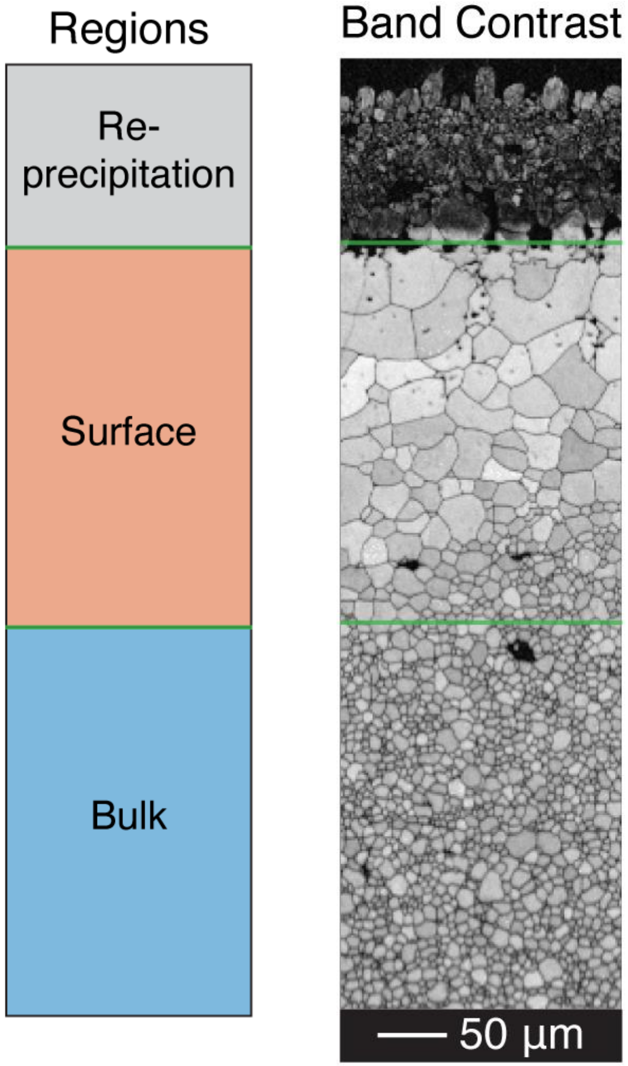
- Larger volumes of YSZ dendrites observed in JSC-1A → higher dissolution rate
- Powder experiments revealed similar solubilities of Zr/Y cations in LHS-1 and JSC-1A
- Higher dissolution rate attributed to order-of-magnitude difference in molten regolith viscosities

Microstructural characterization

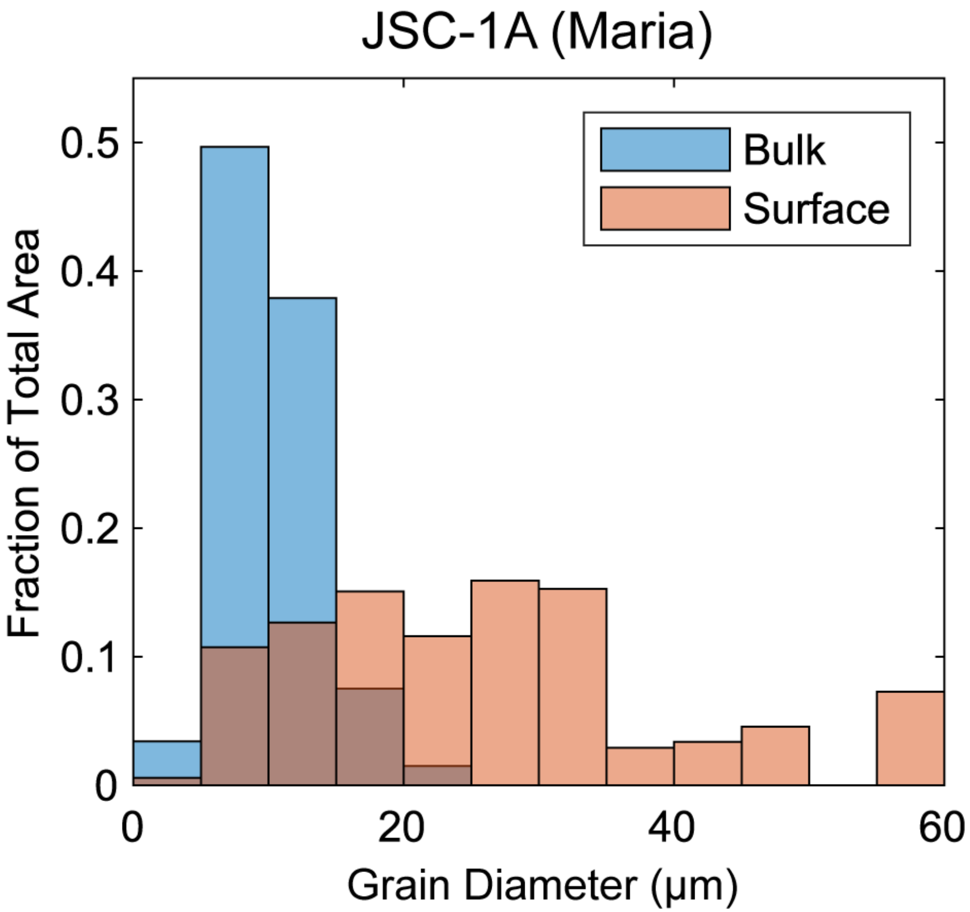
Combined analysis:
- SEM (Backscatter)
- EDS
- EBSD
  - Phase map
  - Band contrast



Grain coarsening – JSC-1A (Maria)



Grain segmentation and grain size analysis



Coarsening observed near YSZ/JSC-1A interface

Summary

Findings

- Powders:
  - YSZ dissolution and Y depletion are primary degradation mechanisms
  - Similar solubilities for Zr/Y cations in both regolith simulants
- Crucibles:
  - Lower viscosity in molten regolith simulants accelerates YSZ dissolution
    - YSZ more suitable for contact with highlands-like (LHS-1) regolith
  - YSZ grain coarsening is significant
    - May extend usable life of crucible

Comparison to TBC/CMAS

- Similarities:
  - CMAS and lunar regolith compositions
  - Dissolution-reprecipitation mechanism causes formation of Y-depleted, transformable YSZ
- Differences:
  - YSZ microstructure
    - Less complexity in crucible system
    - No columnar pores
  - Large sink of regolith
    - Reactive crystallization may not be suitable (EBC)

YSZ can be used in contact with molten regolith for limited durations

Caltech

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Backup

Grain size – Exterior/Bulk/Surface